OPERATING SYSTEMS

Lesson 6: PROCESS SYNCHRONIZATION

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- Background
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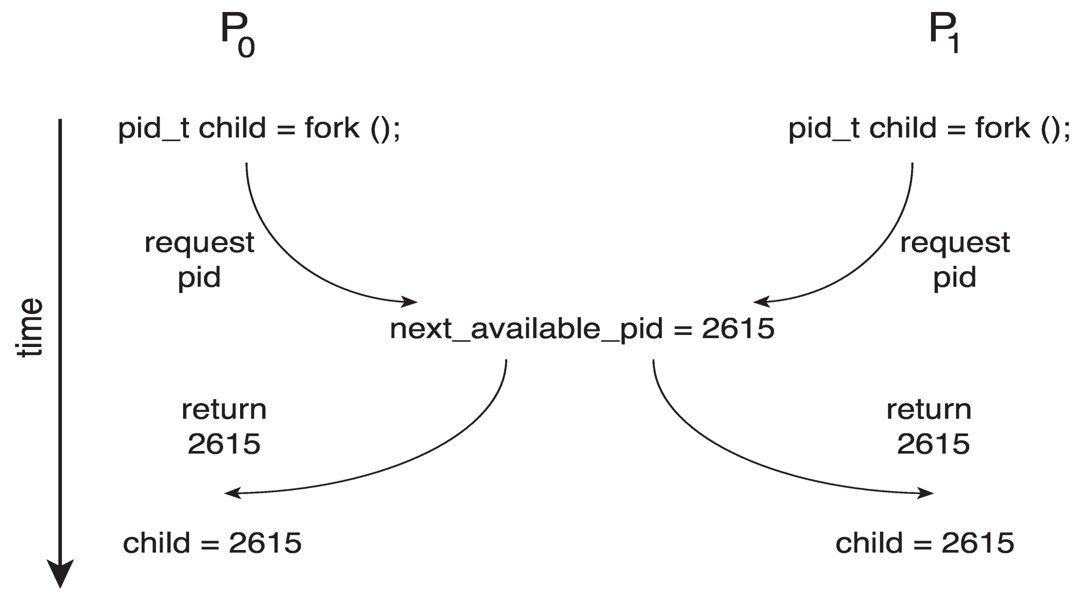
Background

- Processes can execute concurrently
  - May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes

Race Condition

- Processes P_0 and P_1 are creating child processes using the `fork()` system call
- Race condition on kernel variable `next_available_pid` which represents the next available process identifier (pid)



- Unless there is a mechanism to prevent P_0 and P_1 from accessing the variable `next_available_pid` the same pid could be assigned to two different processes!

Producer-Consumer

- Global shared data: **counter, BUFFER[], BUFFER_SIZE**

Nhà sản xuất (P)

```
while (true) { /*  produce an item and put in
nextProduced  */
while (counter == BUFFER_SIZE); // do
nothing
 buffer [in] = nextProduced;
 in = (in + 1) % BUFFER_SIZE;
 counter++;
}
```

Người dùng (C)

```
while (true)  {
 while (counter == 0); // do nothing
nextConsumed =  buffer[out];
 out = (out + 1) % BUFFER_SIZE;
counter--;
/*  consume the item in nextConsumed  */
}
```

- counter++

$register_1 = counter;$

$register_1 = register_1 + 1;$

$counter = register_1;$

- counter--

$register_2 = counter;$

$register_2 = register_2 - 1;$

$counter = register_2;$

T_0:	*producer*	execute	$register_1 = counter$	$\{register_1 = 5\}$
T_1:	*producer*	execute	$register_1 = register_1 + 1$	$\{register_1 = 6\}$
T_2:	*consumer*	execute	$register_2 = counter$	$\{register_2 = 5\}$
T_3:	*consumer*	execute	$register_2 = register_2 - 1$	$\{register_2 = 4\}$
T_4:	*producer*	execute	$counter = register_1$	$\{counter = 6\}$
T_5:	*consumer*	execute	$counter = register_2$	$\{counter = 4\}$

Critical Section Problem

- Consider system of ***n*** processes $\{p_0, p_1, \ldots p_{n-1}\}$
- Each process has **critical section** segment of code
  - Process may be changing common variables, updating table, writing file, etc.
  - When one process in critical section, no other may be in its critical section
- ***Critical section problem*** is to design protocol to solve this
- Each process must ask permission to enter critical section in **entry section**, may follow critical section with **exit section**, then **remainder section**

Critical Section

- General structure of process P_i

```
while (true) {

        entry section

            critical section

        exit section

            remainder section

}
```

Critical-Section Problem (Cont.)

Requirements for solution to critical-section problem

1. **Mutual Exclusion** - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections
2. **Progress** - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the process that will enter the critical section next cannot be postponed indefinitely
3. **Bounded Waiting** - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted
   - Assume that each process executes at a nonzero speed
   - No assumption concerning **relative speed** of the n processes

Interrupt-based Solution

- Entry section: disable interrupts
- Exit section: enable interrupts
- Will this solve the problem?
  - What if the critical section is code that runs for an hour?
  - Can some processes starve – never enter their critical section.
  - What if there are two CPUs?

Peterson's Solution

- Two process solution
- Assume that the **load** and **store** machine-language instructions are atomic; that is, cannot be interrupted
- The two processes share two variables:
  - **int turn;**
  - **boolean flag[2]**

- The variable **turn** indicates whose turn it is to enter the critical section
- The **flag** array is used to indicate if a process is ready to enter the critical section.
  - **flag[i] = *true*** implies that process P_i is ready!

Algorithm for Process P_i

```
while (true){
  flag[i] = true;
  turn = j;
  while (flag[j] && turn = = j)
     ;

     /* critical section */

  flag[i] = false;

  /* remainder section */

}
```

Correctness of Peterson's Solution

- Provable that the three CS requirement are met:
  1. Mutual exclusion is preserved

     P_i enters CS only if:

     either **`flag[j] = false`** or **`turn = i`**
  2. Progress requirement is satisfied
  3. Bounded-waiting requirement is met

Peterson’s Solution and Modern Architecture

- Although useful for demonstrating an algorithm, Peterson’s Solution is not guaranteed to work on modern architectures.
  - To improve performance, processors and/or compilers may reorder operations that have no dependencies
- Understanding why it will not work is useful for better understanding race conditions.
- For single-threaded this is ok as the result will always be the same.
- For multithreaded the reordering may produce inconsistent or unexpected results!

Modern Architecture Example

- Two threads share the data:

```
boolean flag = false;
 int x = 0;
```

- Thread 1 performs

```
while (!flag)
     print x;
```

- Thread 2 performs

```
 x = 100;
 flag = true;
```

- What is the expected output?

100

Modern Architecture Example (Cont.)

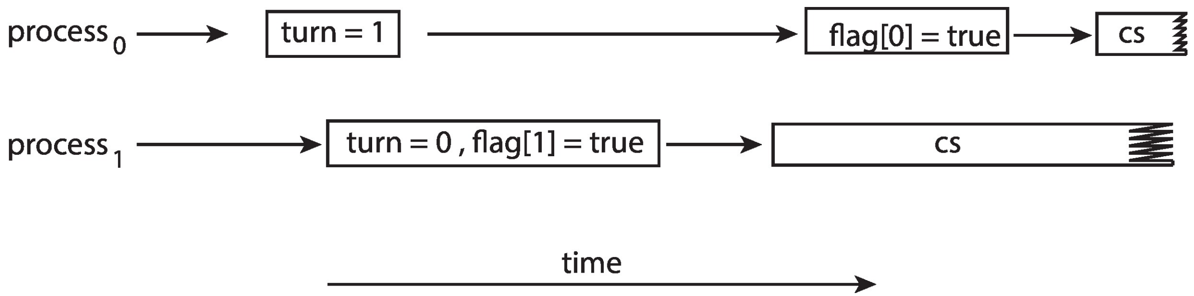
- However, since the variables `flag` and `x` are independent of each other, the instructions:

```
flag = true;
 x = 100;
```

  for Thread 2 may be reordered
- If this occurs, the output may be 0!

Peterson's Solution Revisited

- The effects of instruction reordering in Peterson's Solution



- This allows both processes to be in their critical section at the same time!
- To ensure that Peterson's solution will work correctly on modern computer architecture we must use **Memory Barrier**.

Synchronization Hardware

- Many systems provide hardware support for implementing the critical section code.
- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable
- We will look at three forms of hardware support:

1. Hardware instructions

2. Atomic variables

Hardware Instructions

- Special hardware instructions that allow us to either *test-and-modify* the content of a word, or to *swap* the contents of two words atomically (uninterruptedly.)
  - **Test-and-Set** instruction
  - **Compare-and-Swap** instruction

The test_and_set Instruction

- Definition

```
         boolean test_and_set (boolean
*target)
        {
              boolean rv = *target;
              *target = true;
              return rv:
        }
```

- Properties
  - Executed atomically
  - Returns the original value of passed parameter
  - Set the new value of passed parameter to **`true`**

Solution Using test_and_set()

- Shared boolean variable **lock**, initialized to **false**
- Solution:

```
do {
      while (test_and_set(&lock))
       ; /* do nothing */

           /* critical section */

    lock = false;
           /* remainder section */
 } while (true);
```

- Does it solve the critical-section problem?

The compare_and_swap Instruction

- Definition

```
int compare_and_swap(int *value, int expected, int new_value)
{
    int temp = *value;
   if (*value == expected)
       *value = new_value;
   return temp;
}
```

- Properties
  - Executed atomically
  - Returns the original value of passed parameter **`value`**
  - Set the variable **`value`** the value of the passed parameter **`new_value`** but only if **`*value == expected`** is true. That is, the swap takes place only under this condition.

Solution using compare_and_swap

- Shared integer **`lock`** initialized to 0;
- Solution:

```
    while (true){
      while (compare_and_swap(&lock, 0, 1) != 0)
           ; /* do nothing */

      /* critical section */

      lock = 0;

      /* remainder section */
  }
```

- Does it solve the critical-section problem?

Bounded-waiting with compare-and-swap

```
while (true) {
   waiting[i] = true;
   key = 1;
   while (waiting[i] && key == 1)
      key = compare_and_swap(&lock,0,1);
   waiting[i] = false;
   /* critical section */
   j = (i + 1) % n;
   while ((j != i) && !waiting[j])
      j = (j + 1) % n;
   if (j == i)
      lock = 0;
   else
      waiting[j] = false;
   /* remainder section */
}
```

Atomic Variables

- Typically, instructions such as compare-and-swap are used as building blocks for other synchronization tools.
- One tool is an **atomic variable** that provides *atomic* (uninterruptible) updates on basic data types such as integers and booleans.
- For example:
  - Let **`sequence`** be an atomic variable
  - Let **`increment()`** be operation on the atomic variable **`sequence`**
  - The Command:

```
increment(&sequence);
```

ensures **`sequence`** is incremented without interruption:

Atomic Variables

- The **`increment()`** function can be implemented as follows:

```
void increment(atomic_int *v)
{
    int temp;
    do {
          temp = *v;
    }
      w  h  i  l  e    (  t  e  m  p    !  =
(compare_and_swap(v,temp,temp+1));
}
```

OS

Semaphore

- Synchronization tool that provides more sophisticated ways (than Mutex locks) for processes to synchronize their activities.
- Semaphore ***S*** – integer variable
- Can only be accessed via two indivisible (atomic) operations
  - **`wait()`** and **`signal()`**
    - Originally called **`P()`** and **`V()`**
- Definition of the **`wait() operation`**

```
wait(S) {
    while (S <= 0)
        ; // busy wait
    S--;
}
```

- Definition of the **`signal() operation`**

```
signal(S) {
    S++;
}
```

Semaphore (Cont.)

- **Counting semaphore** – integer value can range over an unrestricted domain
- **Binary semaphore** – integer value can range only between 0 and 1
  - Same as a **mutex lock**
- Can implement a counting semaphore ***S*** as a binary semaphore
- With semaphores we can solve various synchronization problems

Semaphore Usage Example

- Solution to the CS Problem
  - Create a semaphore "**mutex**" initialized to 1

```
wait(mutex);
    CS
signal(mutex);
```

- Consider P_1 and P_2 that with two statements S_1 and S_2 and the requirement that S_1 to happen before S_2
  - Create a semaphore "**synch**" initialized to 0

```
P1:
    S1;
    signal(synch);
P2:
    wait(synch);
    S2;
```

Semaphore Implementation

- Must guarantee that no two processes can execute the `wait()` and `signal()` on the same semaphore at the same time
- Thus, the implementation becomes the critical section problem where the `wait` and `signal` code are placed in the critical section
- Could now have **busy waiting** in critical section implementation
  - But implementation code is short
  - Little busy waiting if critical section rarely occupied
- Note that applications may spend lots of time in critical sections and therefore this is not a good solution

Problems with Semaphores

- Incorrect use of semaphore operations:
  - **`signal(mutex)`** …. **`wait(mutex)`**
  - **`wait(mutex)`** … **`wait(mutex)`**
  - Omitting of **`wait (mutex)`** and/or **`signal (mutex)`**
- These – and others – are examples of what can occur when semaphores and other synchronization tools are used incorrectly.

Liveness

- Processes may have to wait indefinitely while trying to acquire a synchronization tool such as a mutex lock or semaphore.
- Waiting indefinitely violates the progress and bounded-waiting criteria discussed at the beginning of this chapter.
- **Liveness** refers to a set of properties that a system must satisfy to ensure processes make progress.
- Indefinite waiting is an example of a liveness failure.

Liveness

- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Let ***S*** and ***Q*** be two semaphores initialized to 1

P_0	P_1
`wait(S);`	`wait(Q);`
`wait(Q);`	`wait(S);`
`...`	`...`
`signal(S);`	`signal(Q);`
`signal(Q);`	`signal(S);`

- Consider if P_0 executes wait(S) and P_1 wait(Q). When P_0 executes wait(Q), it must wait until P_1 executes signal(Q)
- However, P_1 is waiting until P_0 execute signal(S).
- Since these signal() operations will never be executed, P_0 and P_1 are **deadlocked**.

Liveness

- Other forms of deadlock:
- **Starvation** – indefinite blocking
  - A process may never be removed from the semaphore queue in which it is suspended
- **Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process
  - Solved via **priority-inheritance protocol**

SYNCHRONIZATION EXAMPLES

Classical Problems of Synchronization

- Classical problems used to test newly-proposed synchronization schemes
  - Bounded-Buffer Problem
  - Readers and Writers Problem
  - Dining-Philosophers Problem

Bounded-Buffer Problem

- ***n*** buffers, each can hold one item
- Semaphore **`mutex`** initialized to the value 1
- Semaphore **`full`** initialized to the value 0
- Semaphore **`empty`** initialized to the value n

Bounded Buffer Problem (Cont.)

- The structure of the **producer** process

```
while (true) {
     ...
    /* produce an item in next_produced */
     ...
   wait(empty);
   wait(mutex);
      ...
    /* add next produced to the buffer */
      ...
   signal(mutex);
   signal(full);
}
```

Bounded Buffer Problem (Cont.)

- The structure of the consumer process

```
while (true) {
   wait(full);
   wait(mutex);
      ...
          /* remove an item from buffer to
next_consumed */
      ...
   signal(mutex);
   signal(empty);
      ...
     /* consume the item in next consumed */
      ...
  }
```

Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - **Readers** – only read the data set; they do ***not*** perform any updates
  - **Writers** – can both read and write
- Problem – allow multiple readers to read at the same time
  - Only one single writer can access the shared data at the same time
- Several variations of how readers and writers are considered – all involve some form of priorities

Readers-Writers Problem (Cont.)

- Shared Data
  - Data set
  - Semaphore **`rw_mutex`** initialized to 1
  - Semaphore **`mutex`** initialized to 1
  - Integer **`read_count`** initialized to 0

Readers-Writers Problem (Cont.)

- The structure of a **writer** process

```
while (true) {
    wait(rw_mutex);
        ...
    /* writing is performed */
        ...
    signal(rw_mutex);
}
```

Readers-Writers Problem (Cont.)

- The structure of **a reader** process

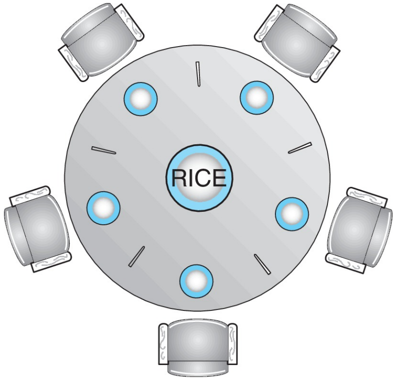
```
while (true){
        wait(mutex);
        read_count++;
        if (read_count == 1) /* first reader */
             wait(rw_mutex);
        signal(mutex);
           ...
              /* reading is performed */
           ...
        wait(mutex);
        read count--;
        if (read_count == 0) /* last reader */
              signal(rw_mutex);
        signal(mutex);
   }
```

Readers-Writers Problem Variations

- The solution in previous slide can result in a situation where a writer process never writes. It is referred to as the "First reader-writer" problem.
- The "Second reader-writer" problem is a variation the first reader-writer problem that state:
  - Once a writer is ready to write, no "newly arrived reader" is allowed to read.
- Both the first and second may result in starvation. leading to even more variations
- Problem is solved on some systems by kernel providing reader-writer locks

Dining-Philosophers Problem

- N philosophers' sit at a round table with a bowel of rice in the middle.



- They spend their lives alternating thinking and eating.
- They do not interact with their neighbors.
- Occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both to eat, then release both when done
- In the case of 5 philosophers, the shared data
  - Bowl of rice (data set)
  - Semaphore chopstick [5] initialized to 1

Dining-Philosophers Problem Algorithm

- Semaphore Solution
- The structure of Philosopher i :

```
while (true){
     wait (chopstick[i] );
    wait (chopStick[ (i + 1) % 5] );

     /* eat for awhile */

    signal (chopstick[i] );
      signal (chopstick[ (i + 1) %
   5] );

     /* think for awhile */

}
```

- What is the problem with this algorithm?

POSIX Semaphores

- POSIX provides two versions – **named** and **unnamed**.
- Named semaphores can be used by unrelated processes, unnamed cannot.

POSIX Named Semaphores

- Creating an initializing the semaphore:

```
#include <semaphore.h>
sem_t *sem;

/* Create the semaphore and initialize it to 1 */
sem = sem_open("SEM", O_CREAT, 0666, 1);
```

- Another process can access the semaphore by referring to its name **SEM**.
- Acquiring and releasing the semaphore:

```
/* acquire the semaphore */
sem_wait(sem);

/* critical section */

/* release the semaphore */
sem_post(sem);
```

POSIX Unnamed Semaphores

- Creating an initializing the semaphore:

```
#include <semaphore.h>
sem_t sem;

/* Create the semaphore and initialize it to 1 */
sem_init(&sem, 0, 1);
```

- Acquiring and releasing the semaphore:

```
/* acquire the semaphore */
sem_wait(&sem);

/* critical section */

/* release the semaphore */
sem_post(&sem);
```

POSIX Condition Variables

- Since POSIX is typically used in C/C++ and these languages do not provide a monitor, POSIX condition variables are associated with a POSIX mutex lock to provide mutual exclusion: Creating and initializing the condition variable:

```
pthread_mutex_t mutex;
pthread_cond_t cond_var;

pthread_mutex_init(&mutex,NULL);
pthread_cond_init(&cond_var,NULL);
```

POSIX Condition Variables

- Thread waiting for the condition **a == b** to become true:

```
pthread_mutex_lock(&mutex);
while (a != b)
    pthread_cond_wait(&cond_var, &mutex);

pthread_mutex_unlock(&mutex);
```

- Thread signaling another thread waiting on the condition variable:

```
pthread_mutex_lock(&mutex);
a = b;
pthread_cond_signal(&cond_var);
pthread_mutex_unlock(&mutex);
```

Java Synchronization

- Java provides rich set of synchronization features:
  - Java monitors
  - Reentrant locks
  - Semaphores
  - Condition variables

Java Monitors

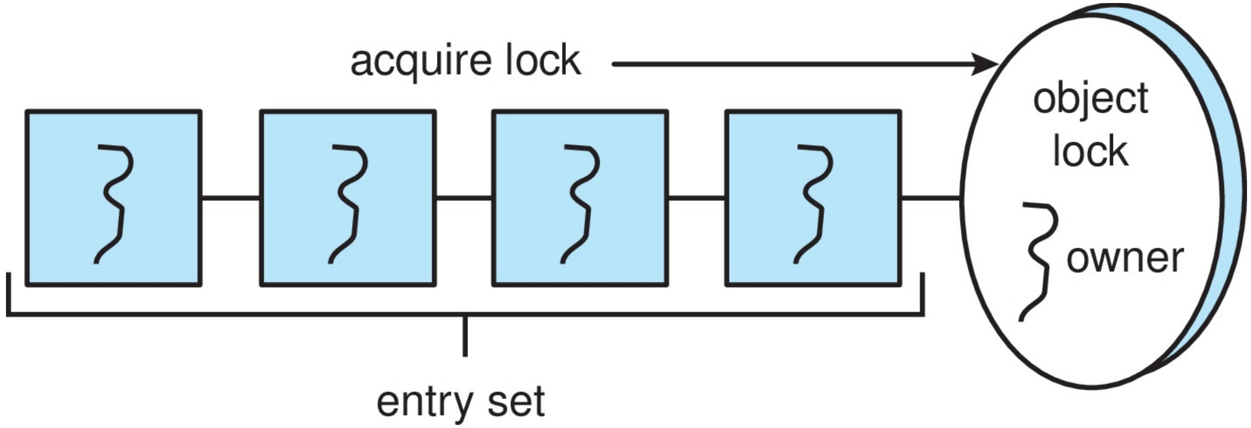
- Every Java object has associated with it a single lock.
- If a method is declared as **`synchronized`**, a calling thread must own the lock for the object.
- If the lock is owned by another thread, the calling thread must wait for the lock until it is released.
- Locks are released when the owning thread exits the **`synchronized`** method.

Bounded Buffer – Java Synchronization

```
public class BoundedBuffer<E>
{
   private static final int BUFFER_SIZE = 5;

   private int count, in, out;
   private E[] buffer;

   public BoundedBuffer() {
      count = 0;
      in = 0;
      out = 0;
      buffer = (E[]) new Object[BUFFER_SIZE];
   }

   /* Producers call this method */
   public synchronized void insert(E item) {
      /* See Figure 7.11 */
   }

   /* Consumers call this method */
   public synchronized E remove() {
      /* See Figure 7.11 */
   }
}
```

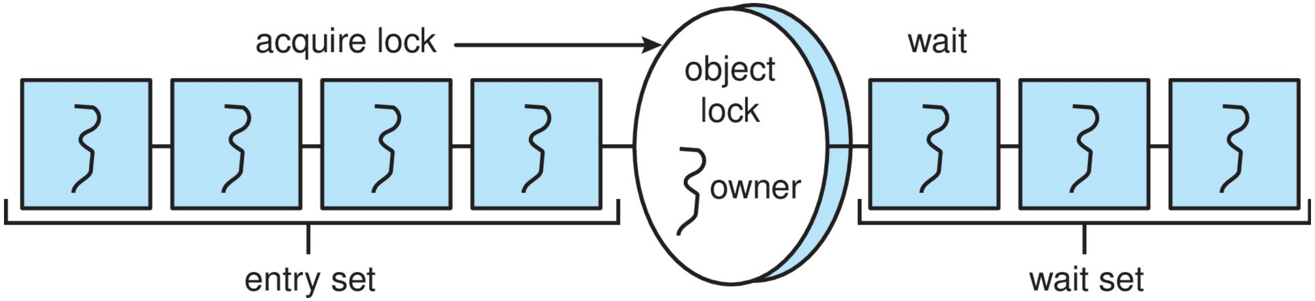
Java Synchronization

- A thread that tries to acquire an unavailable lock is placed in the object's **entry set**:



Java Synchronization

- Similarly, each object also has a **wait set**.
- When a thread calls **`wait()`**:
  1. It releases the lock for the object
  2. The state of the thread is set to blocked
  3. The thread is placed in the wait set for the object



Java Synchronization

- A thread typically calls wait() when it is waiting for a condition to become true.
- How does a thread get notified?
- When a thread calls **`notify()`**:
  1. An arbitrary thread T is selected from the wait set
  2. T is moved from the wait set to the entry set
  3. Set the state of T from blocked to runnable.
- T can now compete for the lock to check if the condition it was waiting for is now true.

Bounded Buffer – Java

Synchronization

```
/* Producers call this method */
public synchronized void insert(E item) {
   while (count == BUFFER_SIZE) {
      try {
         wait();
      }
      catch (InterruptedException ie) { }
   }

   buffer[in] = item;
   in = (in + 1) % BUFFER_SIZE;
   count++;

   notify();
}
```

Bounded Buffer – Java

Synchronization

```
/* Consumers call this method */
public synchronized E remove() {
  E item;

  while (count == 0) {
    try {
      wait();
    }
    catch (InterruptedException ie) { }
  }

  item = buffer[out];
  out = (out + 1) % BUFFER_SIZE;
  count--;

  notify();

  return item;
}
```

Java Reentrant Locks

- Similar to mutex locks
- The **`finally`** clause ensures the lock will be released in case an exception oc

```
Lock key = new ReentrantLock();

key.lock();
try {
   /* critical section */
}
finally {
   key.unlock();
}
```

Java Semaphores

- Construct `Semaphore(int value);`

- Usage:

```
Semaphore sem = new Semaphore(1);

try {
   sem.acquire();
   /* critical section */
}
catch (InterruptedException ie) { }
finally {
   sem.release();
}
```

Java Condition Variables

- Condition variables are associated with an **`ReentrantLock`**.
- Creating a condition variable using **`newCondition()`** method of

```
Lock key = new ReentrantLock();
Condition condVar = key.newCondition();
```

- A thread waits by calling the **`await()`** method, and signals by calling the **`signal()`** method.

Java Condition Variables

- Example:
- Five threads numbered 0 .. 4
- Shared variable **`turn`** indicating which thread's turn it is.
- Thread calls **`doWork()`** when it wishes to do some work. (But it may only do work if it is their turn.
- If not their turn, wait
- If their turn, do some work for awhile …...
- When completed, notify the thread whose turn is next.
- Necess

```
Lock lock = new ReentrantLock();
Condition[] condVars = new Condition[5];

for (int i = 0; i < 5; i++)
   condVars[i] = lock.newCondition();
```

Java Condition Variables

```
/* threadNumber is the thread that wishes to do some work */
public void doWork(int threadNumber)
{
   lock.lock();

   try {
      /**
       * If it's not my turn, then wait
       * until I'm signaled.
       */
      if (threadNumber != turn)
         condVars[threadNumber].await();

      /**
       * Do some work for awhile ...
       */

      /**
       * Now signal to the next thread.
       */
      turn = (turn + 1) % 5;
      condVars[turn].signal();
   }
   catch (InterruptedException ie) { }
   finally {
      lock.unlock();
   }
}
```

Homework

Abraham Silberschatz, Peter Baer Galvin, Greg Gagne, Operating System Concepts, 9th edition, 2013

Compulsory:

- Write a program to solve Producer-Consumer, Reader-Writer, Dinning-Philosophers Problems

Thank you!

Q&A